Chapter 13

Alternating Current Circuits

Chapter 13 is mostly finished, but is not in camera-ready format. This file doesn't have any of the diagrams, but it does have some text-excerpts, with omissions indicated by ..... 

background: This chapter assumes you have studied Sections 11.10 (RC circuits) & 12.5 (LR circuits). strategy: Read Sections 13-1 & 13-2 first. Then, if your class studies the time-dependency of voltage and phasor diagrams (or if you're curious and want to learn), read Sections 13.3 and 13.4.

13.1 Alternating Current

Chapter 11 described the behavior of capacitors & resistors in *direct current* (dc) circuits, where negatively-charged electrons always move in one direction, away from the battery's negative terminal toward its positive terminal.

As described in Section 12.4, electric generators at a power plant produce voltage whose magnitude and direction varies as shown by the *sine curve* on the first graph below. This alternating voltage causes *alternating current* (ac). In an *ac circuit*, electrons move one direction and then the opposite direction, as shown in the second graph, oscillating back and forth about relatively fixed positions.

[ two graphs will be shown here ]

Over one full cycle, ac voltage is positive for \( \frac{1}{2} \) cycle and negative for \( \frac{1}{2} \) cycle. A sine curve is symmetric, so the + and – voltages cancel each other and \( V_{\text{average}} \) is zero. But taking the *root mean square average* (a technique shown in Problem 13-#) gives \( V_{\text{rms}} = V_{\text{max}} / \sqrt{2} = .7071 \ V_{\text{max}} \). Similarly, \( I_{\text{rms}} = .7071 \ I_{\text{max}} \).

In the United States, most ac current that is delivered to houses and businesses alternates at a rate of 60 cycles per second, with \( V_{\text{rms}} \) approximately 120 Volts, so \( V_{\text{peak}} = V_{\text{rms}} / .707 = 120 / .707 = 170 \) Volts.

13.2 Equations for Alternating Current Circuits

The circuit below contains an *ac voltage source* (like an ac generator, or just plugging the circuit into an electrical wall-outlet) with a potential difference of \( \Delta V_S \), an *inductor* "\( \text{L} \)" (I don't have the graphic in this file, so I'll just fill the spaces with INDUCTOR" temporarily) with \( \Delta V_L \) and *inductance* \( L \), and a *resistor* "\( \text{R} \)" with \( \Delta V_R \) and *resistance* \( R \), and a *capacitor" \( \text{C} \)" with \( \Delta V_C \) and *capacitance* \( C \).

[ picture of LRC circuit will be here ]
The rest of Chapter 13 describes the behavior of this type of **LRC series circuit**.

The current and all four potential differences change throughout the cycle. Graphs of I and ΔV have the "continuous sine wave" shape shown in Section 13.1, with *frequency* \( \omega \) and *angular frequency* \( \omega \).

As explained in Section 5.4c, \( \omega = 2\pi f \).

At some point during each ac cycle, the current reaches a maximum \( I_{\text{max}} \). And at some point in the cycle, the voltage across the INDUCTOR, \( \sqrt{\omega} \) and \( \mathbf{I} \) reach a maximum; these maximum voltages are \( \Delta V_{L_{\text{max}}} \), \( \Delta V_{R_{\text{max}}} \) and \( \Delta V_{C_{\text{max}}} \).

At any instant of time, current is the same in every part of a simple series circuit. If charge is moving \( \mathcal{Q} \) at the rate of 2 Coulombs/second through the INDUCTOR, at this instant there is 2 Amps \( \mathcal{Q} \) through the \( \sqrt{\omega} \), and also 2 Amps \( \mathcal{Q} \) to and from the \( \mathbf{I} \).

But \( \Delta V_{L_{\text{max}}} \), \( \Delta V_{R_{\text{max}}} \) and \( \Delta V_{C_{\text{max}}} \) always occur at different times, and usually have different magnitudes. The timing of these ΔV-maximums is discussed in Sections 13.3 & 13.4, along with their relationship to \( \Delta V_{S_{\text{max}}} \). The magnitudes of the ΔV-maximums are given by the equations below, which each has a format of "ΔV = I ( ) ".

\[
\begin{align*}
\Delta V_{L_{\text{max}}} &= I_{\text{max}} XL, \quad \text{where } XL + \omega L \text{ is the inductive reactance of the INDUCTOR.} \\
\Delta V_{R_{\text{max}}} &= I_{\text{max}} R, \quad \text{where } R \text{ is the resistance of the } \sqrt{\omega}. \\
\Delta V_{C_{\text{max}}} &= I_{\text{max}} XC, \quad \text{where } XC + 1/\omega C \text{ is the capacitive reactance of the } \mathbf{I}. \\
\Delta V_{S_{\text{max}}} &= I_{\text{max}} Z, \quad \text{where } Z + \sqrt{R^2 + (XL - XC)^2} \text{ is the impedance of the circuit.}
\end{align*}
\]

In a dc circuit, R is the "resistance" to current flow. Similarly, in an ac circuit Z shows how much the circuit "impedes" the flow of current.

Each element in a circuit contributes to Z, the total impedance of the circuit. The \( \sqrt{\omega} \) contributes resistance R, while INDUCTOR and \( \mathbf{I} \) contribute "reactances" of \( XL \) and \( XC \). If you study Sections 13.3 and 13.4, you'll discover why \( Z \) is not a simple addition of "\( R + XL + XC \)".

\( R, XL, XC \) and \( Z \) have the same units: ohms, \( \Omega \).

\[ \Delta V_L = I_{\text{max}} \omega L; \] This equation shows that an INDUCTOR impedes current most when it has a large inductance L (when it is effective at "fighting") and when the frequency \( \omega \) is large (when current is changing rapidly, thus producing a large ΔI/Δt to "fight against").

The closer a \( \mathbf{I} \) comes to holding its full charge, the more it impedes the flow of current. Two factors that help a \( \mathbf{I} \) reach full charge, and thus impede current, are small \( C \) (capacity to hold charge) and small \( \omega \) (a long time-per-cycle allows charge to flow in one direction for a long time, thus causing a buildup). This is why \( \omega \) and \( C \) are "on the bottom" in the V-formula: \( \Delta V_C = I_{\text{max}} / \omega C \).

For a dc series circuit with \( \omega = 0 \), after a long time INDUCTOR doesn't impede current at all because there are no changes to fight against, but a \( \mathbf{I} \) stops it completely. The X-equations correctly predict these results: substitution of "\( \omega = 0 \)" gives \( XL = \omega L = (0)L = 0 \) [showing that INDUCTOR doesn't impede current] and \( XC = 1/\omega C = 1/(0)C = \infty \) [showing that \( \mathbf{I} \) impedes the current infinitely].

If an ac circuit is missing any standard elements (L, R or C) the above equations can still be used; just substitute \( L = 0, R = 0, \) or \( C = \infty \).
**Resonance**

\[ I_{\text{max}} = \Delta V_{L_{\text{max}}} / Z, \] so current in an ac circuit is maximum when \( Z \) is minimum. The minimum \( Z \) (which is equal to \( \sqrt{R^2 + (X_L - X_C)^2} \)) occurs at resonance, when \( X_L - X_C = 0 \), when \( (\omega L) - (1/\omega C) = 0 \), \( \omega^2 L C = 1 \), and \( \omega = \sqrt{1/LC} \):

\[ \text{ac-circuit resonance, with minimum } Z \text{ and maximum } I_{\text{max}}, \text{ occurs when} \]

\[ \omega_{\text{resonance}} = \sqrt{\frac{1}{LC}} \quad \text{and} \quad f_{\text{resonance}} = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}. \]

Units: \( \omega \) is in radians/s, \( f \) is in cycles/second (also called Hertz, abbreviated Hz).

If a circuit is not resonant, resonance can be achieved by varying \( \omega, L \text{ or } C \).

Problem 13-# shows how resonance is used to "tune" a radio or television.

**Power**

In an LRC circuit, power is dissipated (turned into thermal energy) only in \( R \). The INDUCTOR and \( \text{\textbullet} \) store and release energy, but don't dissipate it. Because only \( R \) (not the entire \( Z \)) causes power dissipation, there is a power factor of \( R/Z \) in ac power formulas. If a circuit could have \( R = 0 \), \( R/Z = 0 \), and no energy would be dissipated. For a resonant circuit, \( Z = \sqrt{R^2 + 0^2} = R \), and \( R / Z = 1 \).

{ Optional: some textbooks describe the power factor as \( \cos \phi \), where \( \cos \phi = (Z/R) \). The meaning of \( \phi \) is discussed in Section 13.4.}

In a dc circuit, \( P \) can be calculated in 3 ways: as \( IV \), \( I^2R \), or \( V^2/R \). To calculate the \( \text{rms average power} \) for a full ac cycle, use any dc power formula, replace \( I \& V \) with \( I_{\text{rms}} \& V_{\text{rms}} \), replace \( R \) with \( Z \), and multiply by the power factor of \( Z/R \):

\[ P_{\text{rms}} = I_{\text{rms}} V_{\text{rms}} \frac{Z}{R} = (I_{\text{rms}})^2 Z \frac{Z}{R} = \frac{(V_{\text{rms}})^2}{Z} \frac{Z}{R} \]

\( P_{\text{rms}} \) can also be found using by using \( I_{\text{max}} \& V_{\text{max}} \) (instead of \( I_{\text{rms}} \& V_{\text{rms}} \)) and multiplying by \( \frac{1}{2} \). Why? Because \( I_{\text{rms}} V_{\text{rms}} = (.707 I_{\text{max}})(.707 V_{\text{max}}) = \frac{1}{2} I_{\text{max}} V_{\text{max}} \). Similarly, \( (I_{\text{rms}})^2 = \frac{1}{2} (I_{\text{max}})^2 \) and \( (V_{\text{rms}})^2 = \frac{1}{2} (V_{\text{max}})^2 \).

Optional: If your class studies instantaneous power (the rate of energy dissipation at an instant of time), use the instantaneous values of \( I \& V \): \( P_{\text{instantaneous}} = I_{\text{inst}} V_{\text{inst}} (R/Z) = I_{\text{inst}}^2 Z (R/Z) = (V_{\text{inst}}^2/Z)(R/Z) \). The time-dependence of \( I \& V \) is discussed in Sections 13.3-13.4.

There are many formulas, but they're just familiar dc formulas with 2 changes: replace \( R \) with \( Z \), multiply by \( R/Z \). Use \( \text{rms-values} \) to get \( P_{\text{rms}} \), or use \( \text{max-values} \) and multiply by \( \frac{1}{2} \). Optional: to find \( P_{\text{inst}} \), substitute instantaneous-values.

**PROBLEM 13-A**

An LRC series circuit with \( L = 80 \text{ mH}, R = 20 \Omega \), and \( C = 50 \text{ μF} \), is driven by a 60 Hz source with an average voltage of 120 V. Find the circuit's inductive reactance, capacitive reactance, impedance, maximum current, maximum voltage across each circuit element, and average power. How can you change the \( \text{\textbullet} \) 's capacitance to get a "resonant circuit"?
SOLUTION 13-A

Translate words into variable-letters, choose a formula, substitute-and-solve:

inductive reactance \( X_L = \omega L = 2\pi f L = (2\pi)(60)(80 \times 10^{-3}) = 30.2 \Omega \),

capacitive reactance \( 1/\omega C = 1/2\pi f C = 1/[(2\pi)(60)(50 \times 10^{-6})] = 53.1 \Omega \),

impedance \( = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{20^2 + (30.2 - 53.1)^2} = 30.4 \Omega . \)

From Section 13.1, \( \Delta V_{S_{\text{max}}} = \Delta V_{S_{\text{rms}}} / .707 = (120)/.707 = 170 \text{ V} \).

maximum current \( I_{\text{max}} = (\Delta V_S)_{\text{max}} / Z = 170 / 30.4 = 5.59 \text{ Coulombs/s} \).

maximum voltages:

\[
\Delta V_{L_{\text{max}}} = I_{\text{max}} (X_L) = (5.59)(30.2) = 169 \text{ V}, \\
\Delta V_{R_{\text{max}}} = I_{\text{max}} (R) = (5.59)(20) = 112 \text{ V}, \\
\Delta V_{C_{\text{max}}} = I_{\text{max}} (X_C) = (5.59)(53.1) = 297 \text{ V}.
\]

\[
\begin{align*}
P_{\text{rms}} &= I_{\text{rms}} V_{\text{rms}} (R/Z) \\
&= (.707 I_{\text{max}})(.707 V_{\text{max}}) (R/Z) \\
&= (.707)(5.59)(.707)(170)(20 / 30.4) = 313 \text{ Watts,}
\end{align*}
\]

\[
\begin{align*}
P_{\text{rms}} &= \frac{1}{2} I_{\text{max}} V_{\text{max}} (R/Z) \\
&= \frac{1}{2} (5.59)(170)(20 / 30.4) = 313 \text{ Joules/second}
\end{align*}
\]

For resonance, \( \omega^2 LC = 1 \), \( ([2\pi][60])^2 (80 \times 10^{-3})C = 1 \), \( C = 8.79 \times 10^{-5} \text{ F} = 879 \mu\text{F} \).

Most equations in this section are for the "cycle as a whole". If your class studies instantaneous equations (that describe what is happening at an instant of time) and the time-dependence of voltage, read optional Sections 13.3 & 13.4. { No matter what your class does, you may find it helpful to read Section 13.3, which is short, intuitive and non-mathematical. }

13.3 Time-Dependence of Voltage Maximums

Sections 12.5 and 11.10 discuss LR and RC circuits. When the switch is closed in the LR circuit below, INDUCTOR produces \( \Delta V_L \) to fight the change in current. After a long time, \( I \) through \( \sqrt{\cdot} \) has reached its maximum value and \( \Delta V_R \) is a maximum; \( \Delta I/\Delta t = 0 \) so there is no need for INDUCTOR to "fight", and \( \Delta V_L = 0 \). Notice the order of voltages: first the maximum \( \Delta V_L \) occurs, then the maximum \( \Delta V_R \).

In the rest of Chapter 13, I'll often shorten \( \Delta V \) to \( V \), but remember that \( V \) is a potential difference.

When the switch first closes in the RC circuit, \( I \) and \( V_R \) are maximum. After a long time the fully charged \( I \) has maximum \( V_C \), but no current flows through the \( I \) (or \( \sqrt{\cdot} \) so \( V_R = 0 \). First \( V_R \) occurs, then \( V_C \).

When the switch closes on the LRC circuit, maximum \( V_L \) occurs first (as INDUCTOR reacts to fight the change) but \( V_R \) and \( V_C \) are zero. Then current increases and reaches a maximum, and so does \( V_R \). Finally the current stops because \( I \) is fully charged, with maximum \( V_C \); \( I \) is constant at zero, so \( V_L \) and \( V_R \) are zero. The order of voltage maximums is \( V_L, V_R \) and \( V_C : L \ R \ C \).

[ picture of LRC circuit will be here ]
If the dc battery is replaced by an ac voltage source, current and voltages will change continuously. But the order of V-maximums is the same as in a dc circuit: first $\Delta V_{L_{\text{max}}}$ occurs, followed $\frac{1}{4}$ cycle later by $\Delta V_{R_{\text{max}}}$ and $I_{\text{max}}$, followed $\frac{1}{2}$ cycle later by $\Delta V_{C_{\text{max}}}$. The relationship between these V-maximums and $\Delta V_{S_{\text{max}}}$ is discussed in Section 13.4.

The connection between statements (like "$V_L$ leads $I$" or "$I$ lags behind $V_L$") and graphs (like $V_L$-versus-time) can be confusing. Section 13.4 shows an easy, logical way to understand these graphs.

The order of circuit elements doesn't matter. These circuits all behave the same:

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13.4 Phasor Diagrams, Graphs, Phase Angles, and Time-Dependent Equations

Voltage relationships can be seen easily on a *phasor diagram*. The length of the L, R and C arrows (labeled on the first diagram below) represent the magnitudes of $\Delta V_{L_{\text{max}}}$, $\Delta V_{R_{\text{max}}}$ and $\Delta V_{C_{\text{max}}}$, respectively. The vertical component of the L, R and C arrows (these can be called the *projections* of the arrows onto the vertical axis) show the values of $V_L$, $V_R$ and $V_C$ at a certain instant of time. The first diagram shows what is happening at the instant we define to be $t = 0$. Look at the tips of the R-arrow in the five diagrams. Do you see it make steady progress around the circle? Do you see the relationship between the height of the R-arrow's tip and height of the $V_R$ curve? { Just as we did in Section 8.2 for *simple harmonic motion*, we can take advantage of the fact that when an object moves around a circle at constant speed, the vertical component of its position imitates a "sine wave".

You can use this same process to understand the sine curves for $V_L$ and $V_C$.

A phasor diagram is like 3 cars, spaced $\frac{1}{4}$ cycle apart, moving around circles with different radii. The $V_L$ car peaks first, then $V_R$, $V_C$ and the empty spot (with no V-arrow). This multiple-cyclic process can be described as: $L R C o L R C o L R C o ...$

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Note: If your textbook uses phasor diagrams where V is represented by the horizontal (not vertical) component of $V_{\text{max}}$, just substitute "horizontal" for "vertical" in my descriptions.

At any instant, current is the same in every part of a circuit. $I$ and $\Delta V_R$ reach their maximum value at the same time; they are "in phase with each other".

The first graph below shows that .....[snip].....
The second graph shows that ..... [pictures] .....
Kirchoff’s law is true for "instantaneous" voltages, but not for "maximum" voltage:
\[ \Delta V_{\text{L max}} + \Delta V_{\text{R max}} + \Delta V_{\text{C max}} \neq \Delta V_{\text{S max}}. \]

The four main equations of Section 13.2 have the same format: \( \Delta V_{\text{max}} = I_{\text{max}}(\cdot) \) ..... 

Don't confuse visual-mathematical symbolism with reality. In Section 8.2 the movement of a race car around a circle is used to describe *simple harmonic motion* in equations, even though the object (a block moving back and forth) is not really moving in a circle. Similarly, we can use phasor diagrams to develop equations for the time-dependence of \( \Delta V \), even though the 4 voltages don't really move in a circle like the 4 arrow-tips do. And we add \( V_{\text{max}} \) arrows (for \( V_L \), \( V_R \) and \( V_C \)) as vectors to get the correct \( V_{\text{S max}} \), even though voltages aren't vectors.

**the Phase Angle "\( \phi \)"

If we define \( t + 0 \) when \( V_L \) is maximum (as in the earlier phasor diagrams) and \( \theta + 0 \) as the location of \( V_R \) at this time, then \( \phi \) gives the angular position of \( V_S \) at this \( t + 0 \) instant, and \( \phi \) is a *phase angle*. \( \theta \) and \( \phi \) are defined the same as in Section 8.2!

In the first diagram below, drawn at \( t + 0 \) when \( V_R \) is maximum, \( V_{\text{L max}} \) is larger than \( V_{\text{C max}} \) so the \( V_S \) arrow is ahead of the \( V_R \) arrow, and \( \phi \) is +.

In the second diagram, \( V_{\text{C max}} \) is larger than \( V_{\text{L max}} \); \( V_S \) is behind \( V_R \) and \( \phi \) is −.

\( \Delta V_L \) fights and delays the buildup of current. It is the deciding factor if \( \Delta V_{\text{L max}} \) is larger than \( \Delta V_{\text{C max}} \), as in the first diagram; this causes the maximum of \( I\text{-and-}V_R \) to occur after the maximum of \( V_S \).

The effect of \( \Delta V_C \) is opposite that of \( \Delta V_L \). In the second diagram \( \Delta V_C \) is the most important factor, so its "anti-delay" makes \( I_{\text{max}} \) (and \( \Delta V_{\text{R max}} \)) occur before \( \Delta V_{\text{S max}} \). Because of the way \( \phi \) is defined, instead of saying "\( V_{\text{R max}} \) is ahead of \( V_{\text{S max}} \)" we can state the same fact as "\( V_{\text{S max}} \) is behind \( V_{\text{R max}} \)". which means that \( \phi \) is −.

[ diagrams will be here ]

As described earlier, the \( V_{\text{max}} \)-triangle and XRZ-triangle have the same shape and same \( \phi \), so we could draw the analogous XRZ (instead of \( V_{\text{max}} \)) triangle and use this same "ahead or behind" logic to reach the following useful conclusions.

When \( X_L \) is larger than \( X_C \), the circuit's reactance is "inductive" and \( \phi \) is +.
When \( X_C \) is larger than \( X_L \), the circuit's reactance is "capacitive" and \( \phi \) is −.
When \( X_L \) equals \( X_C \), the circuit is "resonant" with no reactance, and \( \phi \) is zero.

"\( \phi = \tan^{-1} \left[ (X_L - X_C) / R \right] \)" gives the correct \( \phi \), including the correct ± sign.

**Time-Dependent Equations**

To understand the equations below, think about this step-by-step derivation:

Each \( V_{\text{instantaneous}} \) is the vertical component of the \( V_{\text{max}} \) phasor arrow, so \( V_{\text{instantaneous}} = V_{\text{max}} \sin[\text{angular } \theta\text{-position of } V_{\text{max}} \text{ phasor arrow}]. \)

\((\theta\text{-position of arrow}) = \omega t + \theta_i \), where \( \theta_i \) is the position when \( t + 0 \).

When \( t + 0 \), the \( V_L \)-arrow is at +\( \frac{\pi}{2} \), \( V_R \)-arrow is at 0, \( V_C \)-arrow is at −\( \frac{\pi}{2} \), \( V_S \)-arrow is at +\( \phi \), and I (which is in-phase with the \( V_R \)-arrow) is at 0.
\[\Delta V_L = \Delta V_{L_{\text{max}}} \sin(\omega t + \frac{\pi}{2}) = +\Delta V_{L_{\text{max}}} \cos(\omega t)\]
\[\Delta V_R = \Delta V_{R_{\text{max}}} \sin(\omega t)\]
\[\Delta V_C = \Delta V_{C_{\text{max}}} \sin(\omega t - \frac{\pi}{2}) = -\Delta V_{C_{\text{max}}} \cos(\omega t)\]
\[\Delta V_S = \Delta V_{S_{\text{max}}} \sin(\omega t + \phi)\]
\[I = I_{\text{max}} \sin(\omega t)\]

These equations can be "linked" with all equations from Section 13.2 that contain \(\Delta V_{L_{\text{max}}}, \Delta V_{R_{\text{max}}}, \Delta V_{C_{\text{max}}}, \Delta V_{S_{\text{max}}}\) or \(I_{\text{max}}\). Also, \(\omega = 2\pi f\).

If your textbook uses horizontal (not vertical) components of the V-arrows, or if it defines \(t_{\text{0}}\) at a different time (for example, when \(V_S\) is a maximum), its equations will differ from the equations above. But the basic principles are identical, and when used correctly either set of equations will give correct answers.

### 13.90 Memory-Improving Flash Cards

13.1 In a dc circuit, electrons __ .
In an ac circuit, electrons __ .

13.1 The shape of a V(or I)-versus-t graph is __ .

13.1 \(V_{\text{rms}} = __ \), so \(V_{\text{max}} = __ \). \(I_{\text{rms}} = __ \).

13.2 Maximum values of \(V_L, V_R\) & \(V_C\) occur at __ .
At every instant, current is __ .

13.2 \(V_{\text{max}}\) equations for \(L, R, C\) & \(S\) have form __ ,
where [ ] is __ , which all have __ .
__ and __ both contribute to __ ,
which indicates __ .

13.2 An inductor has large \(\Delta V_L\) when it __ ,
and impedes most when __ , so __ .
A capacitor has near-max \(\Delta V_C\) when it __ ,
and impedes most when __ , so __ .
At __ frequency, __ is most important. (2)

13.2 If ac circuit is missing LRC elements, __ .

13.2 Max __ occurs at min __ , which is called __ .
This occurs when __ .
__ is larger than __ . To convert, __ or __ .

always move in the same direction
alternate directions (oscillate back & forth)
sine wave (is assumed for all of Chapter 13)

\(.707 V_{\text{max}}, V_{\text{rms}}/.707, .707 I_{\text{max}}\)

behavior of a series LRC circuit
different times
equal in every part of a series circuit
\(\Delta V_{\text{max}} = I_{\text{max}} [ ]\)
\(X_L, R, X_C\) or \(Z\); same units (ohms, \(\Omega\))
reactance-X's, resistance-R, impedance-Z
how much a circuit impedes ac current flow
fights against current-changes
large \(L\) and high \(f\), \(X_L = \omega L\)
is close to holding its full charge
small \(C\) and low \(f\), \(X_C = 1/\omega C\)
high, \(L\); low, \(C\)
substitute \(L = 0, R = 0, C = \infty\)
\(I_{\text{max}}, Z\), resonance
\(X_L = X_C, \omega^2LC = 1, \omega = \sqrt{1/LC}\)
\(\omega, f, \omega = 2\pi f, \omega / 2\pi = f\)
13.2 In LRC, __ dissipates energy, __ __ energy.  
To get P-formulas, use __ , then __ __ __, which is the __ .  
To get P\textsubscript{root-mean-square}, substitute __ or __ .  
Optional: To get P\textsubscript{instantaneous}, substitute __ .

13.3 V\textsubscript{max} order: in LR __ , in RC __ , in LRC __ .  
Starting with __ , there is __ between __ .  
Circuit behavior doesn't depend on the __ .

13.4 A phasor diagram is analogous to __ .  
If V\textsubscript{S} is also drawn, there are __ that are __ .

13.4 At any instant __ is same thru circuit, __ aren't. __ are always in phase. V-cycle is __ .

13.4 V\textsubscript{maximum} is __ , V\textsubscript{instantaneous} is __ .

phasor & graph: same __ for __ & __ .

13.4 To interpret graph correctly, ask __ not __ .

13.4 __ = __ for __ but not for __ .

13.4 right triangle: legs are __ , hypotenuse is __ ,  
or legs are __ , hypotenuse is __ .  
These triangles ( __ ) are __ so they have __ .

13.4 I\textsubscript{max} always occurs after __ and before __ .  
If __ (so __ ), V\textsubscript{Smax} occurs __ I\textsubscript{max}, \( \phi \) is __ .  
\{ repeat for 3 possibilities \}

Eventually, Chapter 13 will be "finished" in a camera-ready format.